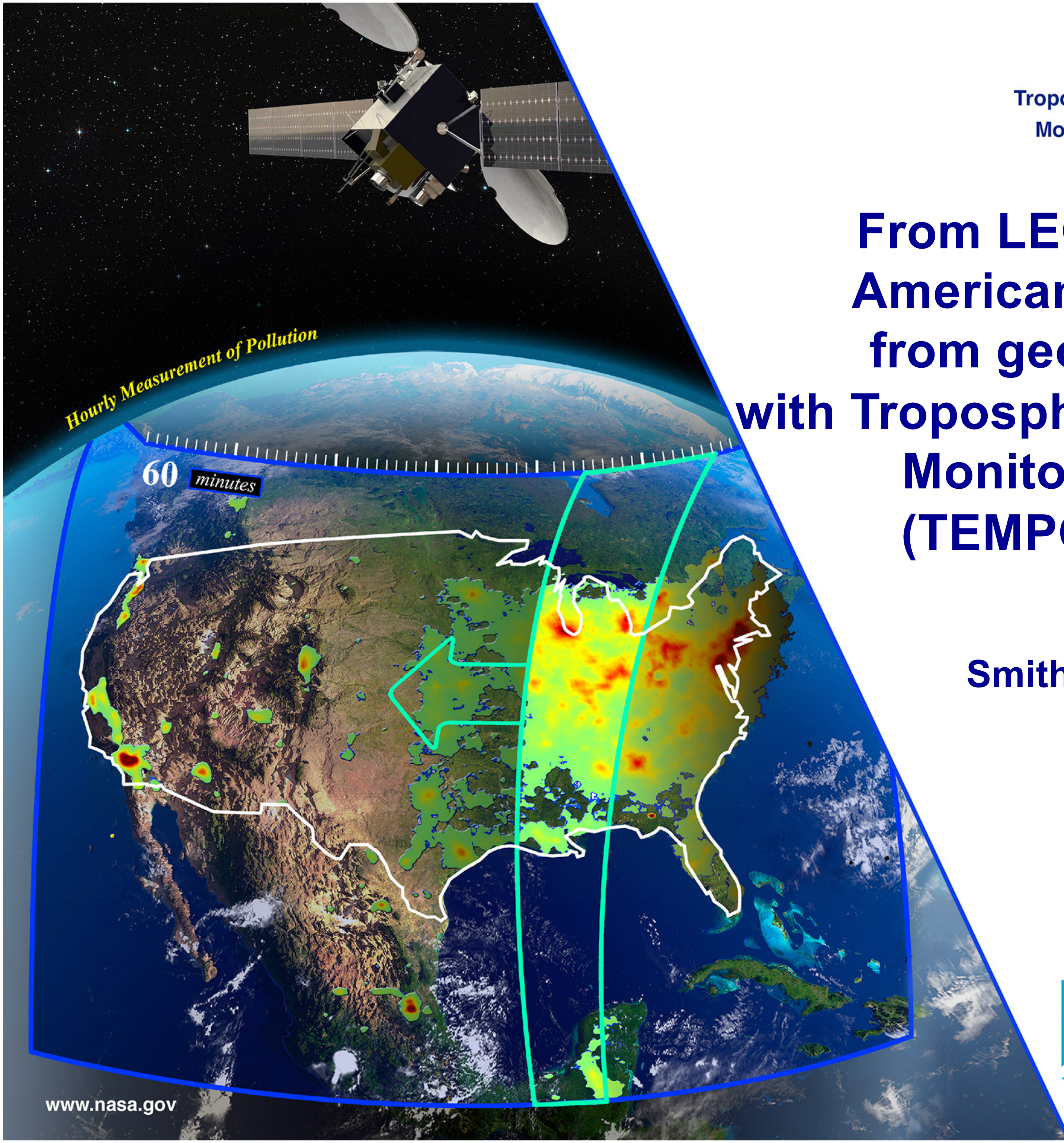


Tropospheric Emissions:
Monitoring of Pollution

From LEO to GEO: North American measurements from geostationary orbit with Tropospheric Emissions: Monitoring of Pollution (TEMPO, tempo.si.edu)

Kelly Chance
Smithsonian Astrophysical Observatory

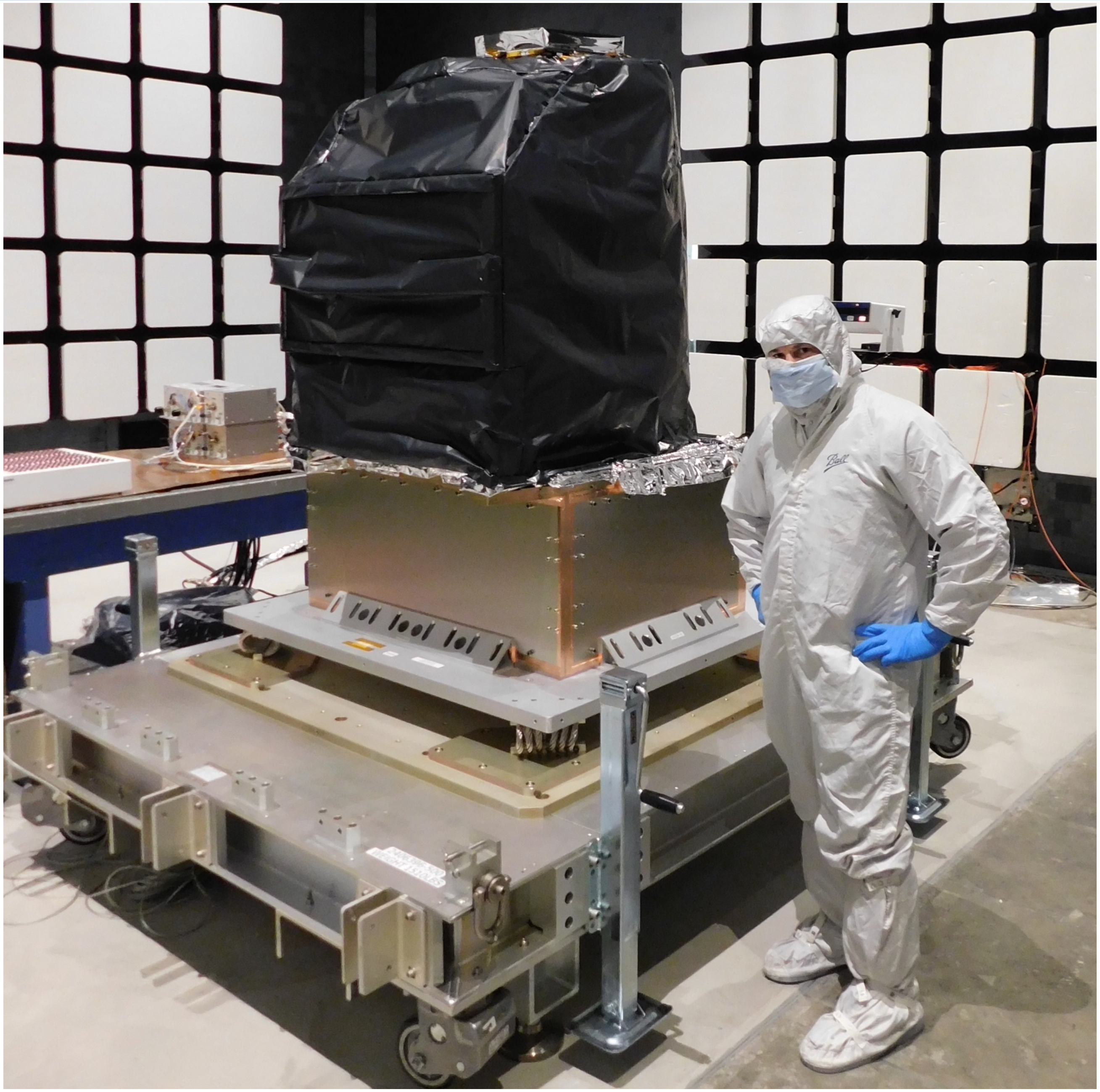
August 29, 2019

Smithsonian

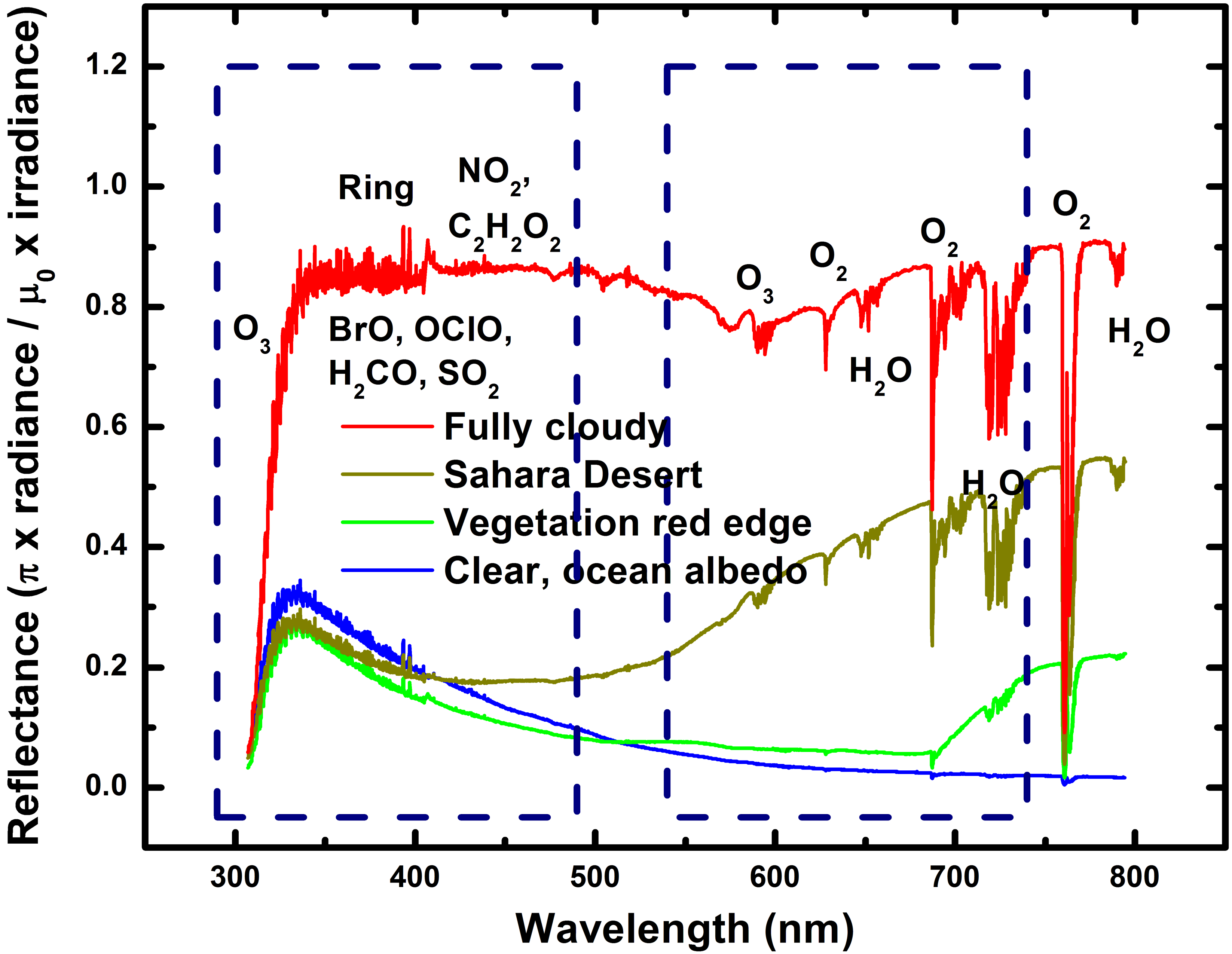
TEMPO status

- **Instrument completed August 23, 2018, now in storage**
- **System Acceptance Review October 11-12**
  - **TEMPO is now officially delivered**
- **Commercial geostationary satellite host to be selected for launch in February 2022 to 92.85°W**

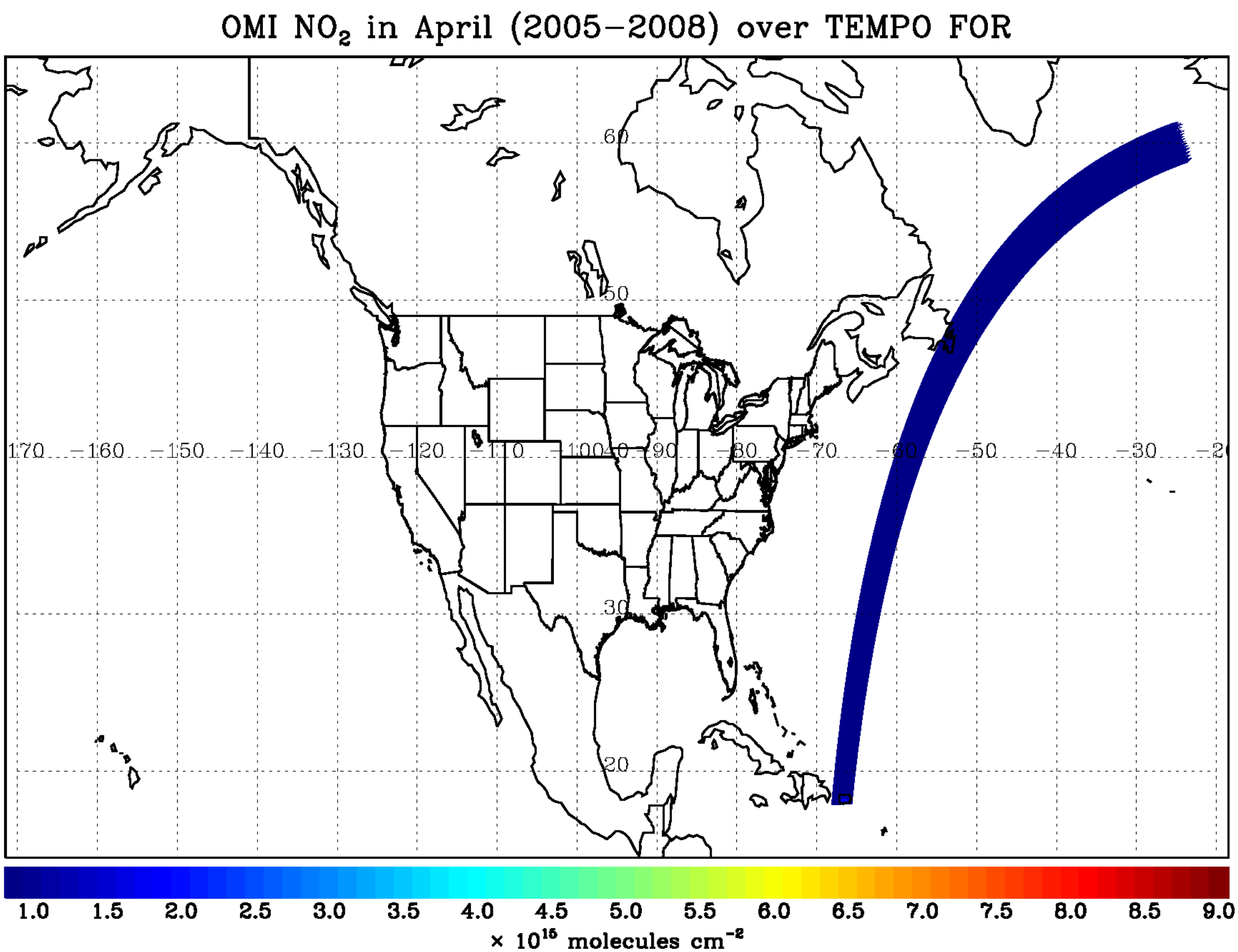
Ready for storage



Typical TEMPO-range spectra (from ESA GOME-1)



TEMPO hourly NO_2 sweep (GEO @92.85W)



Boresight: 33.8°N, 93°W

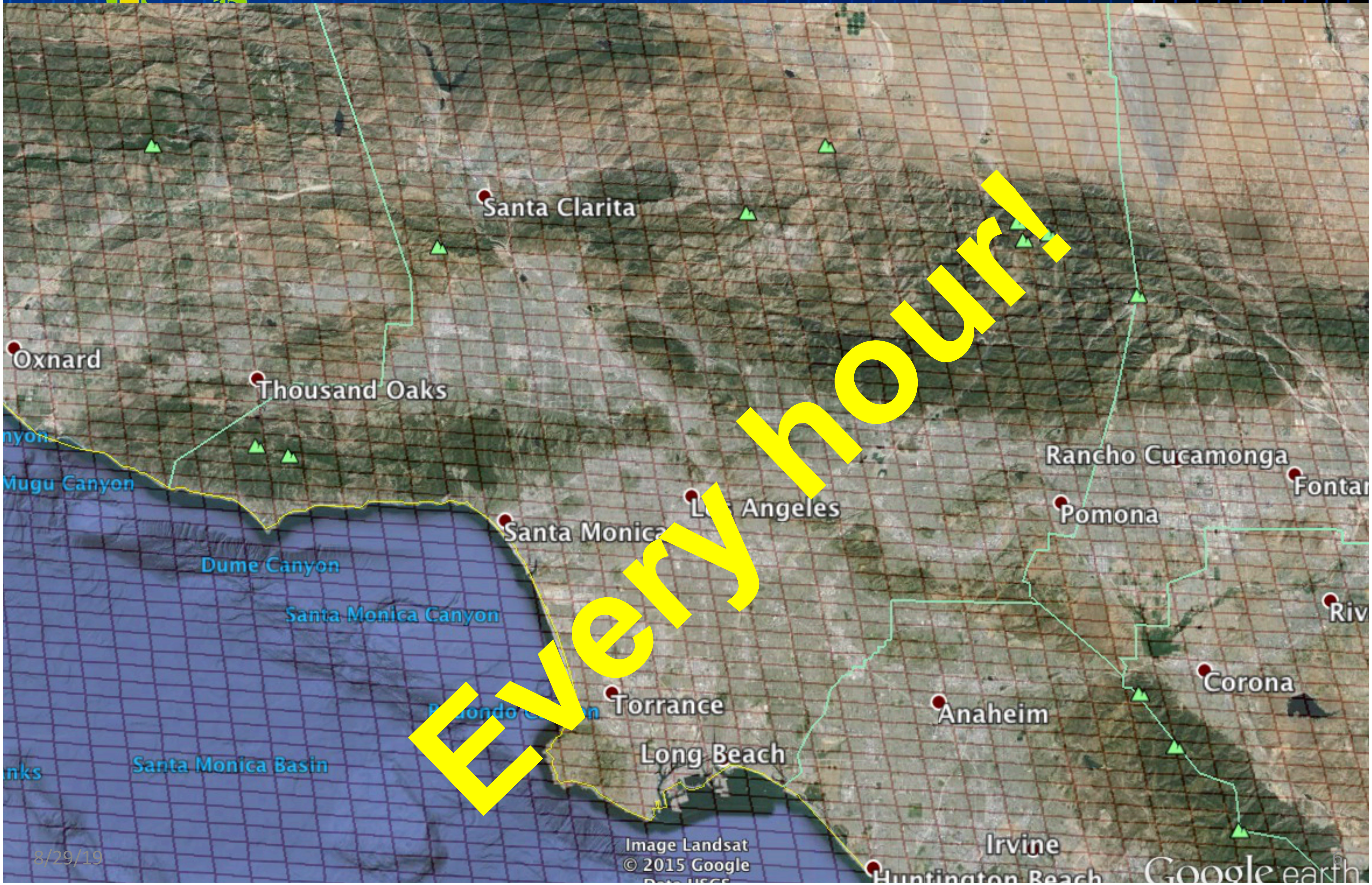
2034 good N/S pixels

- **~ 1282 scans/hr**
- **~ 2.6 M pixels/hr**

Data rate: ~31.2 Mbs

~20 times of OMI data volume (comparable to TROPOMI)

Los Angeles coverage



SAO developments for atmospheric UV/Vis measurements from space

Instrument	Launch	New physics for atmospheric spectroscopy	First molecule measurements
pre-SCIAMACHY – JB, WS, KC (Thanks to the late Dieter Perner!)	1985	O_3 profiling technique, global BrO (Christoph Brühl)	
GOME-1	1995	Solar reference spectrum, Ring effect with O_2 $^3\Sigma$, In-flight wavelength and slit calibration, Grid interpolation of reference spectra, Undersampling correction, Common-mode correction, Direct radiance fitting, Nyquist sampling test	O_3 profiles/trop, BrO, H_2CO
SCIAMACHY	2002	Adoption of improved O_3 cross sections (Bass-Paur)	IO
OMI	2004	Oversampling to improve spatial sampling (Lei Zhu, Kang Sun, et al.)	$C_2H_2O_2$, H_2O 7v polyad (blue)
GOME-2a	2006		
GOME-2b	2012		
OMPS-1	2011	Revised H_2CO cross sections, Revised O_3 cross sections (BDM)	
TROPOMI	2017		
GEMS	2020	Improved solar reference spectrum, with Ewha Womans University	
Sentinel-4	2021+		
TEMPO	2022	Planetary boundary layer O_3	

The TEMPO Green Paper

Chemistry, physics, and meteorology experiments with the Tropospheric Emissions: Monitoring of Pollution instrument

Now at: https://www.cfa.harvard.edu/atmosphere/publications.html

K. Chance[a], X. Liu[a], C. Chan Miller[a], G. González Abad[a], G. Huang[b], C. Nowlan[a], A. Souri[a], R. Suleiman[a], K. Sun[c], H. Wang[a], L. Zhu[a], P. Zoogman[a], J. Al-Saadi[d], J.-C. Antuña-Marrero[e], J. Carr[f], R. Chatfield[g], M. Chin[h], R. Cohen[i], D. Edwards[j], J. Fishman[k], D. Flittner[d], J. Geddes[l], M. Grutter[m], J.R. Herman[n], D.J. Jacob[o], S. Janz[h] J. Joiner[h], J. Kim[p], N.A. Krotkov[h], B. Lefer[q], R.V. Martin,[a,r,s], O.L. Mayol-Bracero[t], A. Naeger[u], M. Newchurch[u], G.G. Pfister[j], K. Pickering[v], R.B. Pierce[w], C. Rivera Cárdenas[m], A. Saiz-Lopez[x], W. Simpson[y], E. Spinei[z], R.J.D. Spurr[aa], J.J. Szykman[bb], O. Torres[h], J. Wang[cc]

NORMAL TIME RESOLUTION STUDIES	Volcanoes
Air quality and health	Socio-economic studies
Ultraviolet exposure	National pollution inventories
Biomass burning	Regional and local transport of pollutants
Synergistic GOES-16/17 Products	Sea breeze studies for Florida and Cuba
Advanced aerosol products	Transboundary pollution gradients
Soil NO_x after fertilizer application and after rainfall	Transatlantic dust transport
Solar-induced fluorescence from chlorophyll	HIGH TIME RESOLUTION EXPERIMENTS
Foliage studies	Lightning NO_x
Mapping NO_2 and SO_2 dry deposition at high resolution	Morning and evening higher-frequency scans
Crop and forest damage from ground-level ozone	Dwell-time studies and temporal selection to improve detection limits
Halogen oxide studies in coastal and lake regions	Exploring the value of TEMPO in assessing pollution transport during upslope flows
Air pollution from oil and gas fields	Tidal effects on estuarine circulation and outflow plumes
Night light measurements resolving lighting type	Air quality responses to sudden changes in emissions
Ship tracks, drilling platform plumes, and other concentrated sources.	Cloud field correlation with pollution
Water vapor studies	Agricultural soil NO_x emissions and air quality

TEMPO

The end!

Thanks to NASA, ESA, Ball Aerospace & Technologies Corp.

Smithsonian

NASA

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INSTITUTO NACIONAL DE ECOLOGÍA Y CAMBIO CLIMÁTICO

INSMET

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION U.S. DEPARTMENT OF COMMERCE

NOAA

Ball

UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

POR MI RAZA HABLARA EL ESPIRITU

DALHOUSIE UNIVERSITY

AD MAJOREM DEI GLORIAM

IHS

1818

SAINT LOUIS UNIVERSITY

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

THE UNIVERSITY OF CALIFORNIA

LET THERE BE LIGHT

1868

UAH

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

HARVARD UNIVERSITY

ATMOSPHERIC CHEMISTRY MODELING GROUP

YONSEI UNIVERSITY

1885

연세대학교

UNIVERSITY OF MARYLAND BALTIMORE COUNTY

UMBC

1966

CSIC

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

THE UNIVERSITY OF IOWA

YORK U

UNIVERSITÉ
UNIVERSITY

NCAR

THE UNIVERSITY OF EDINBURGH

FINNISH METEOROLOGICAL INSTITUTE

CARR ASTRONAUTICS

Science at work

RTS

KNMI

Environment and Climate Change Canada

Environnement et Changement climatique Canada

TEMPO

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Science at work

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Environment and Climate Change Canada
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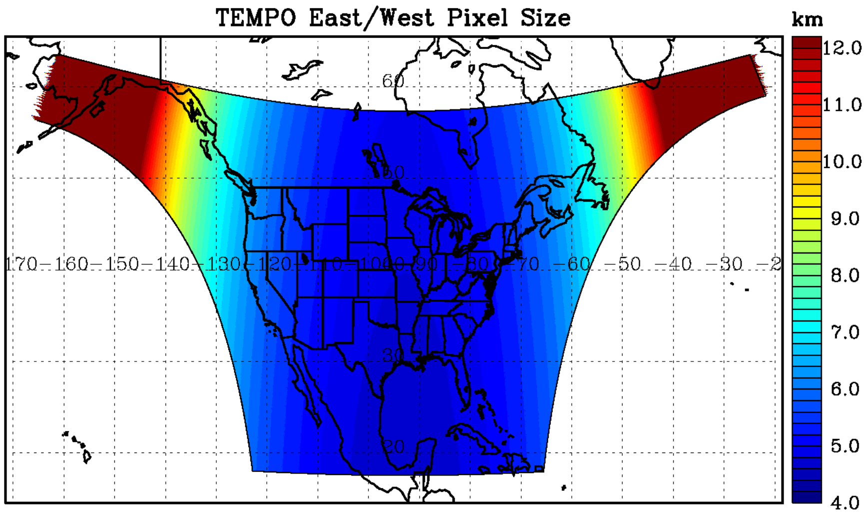
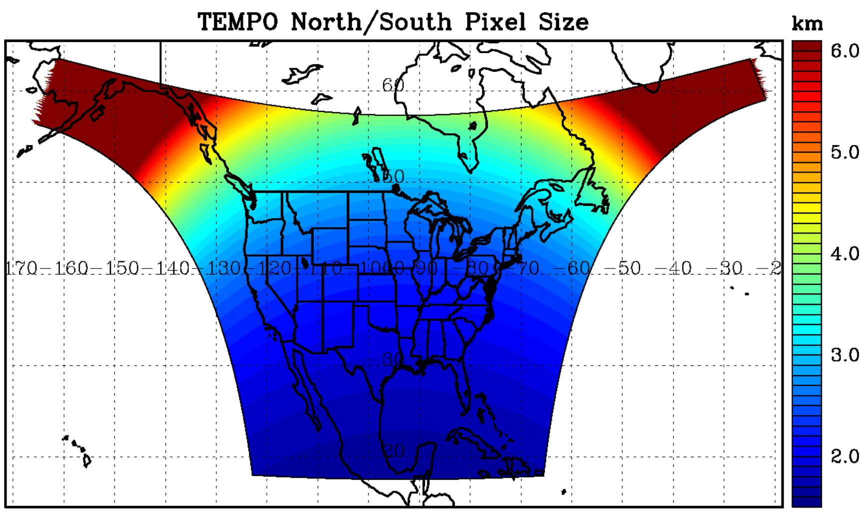
TEMPO footprint (GEO @92.85° W)

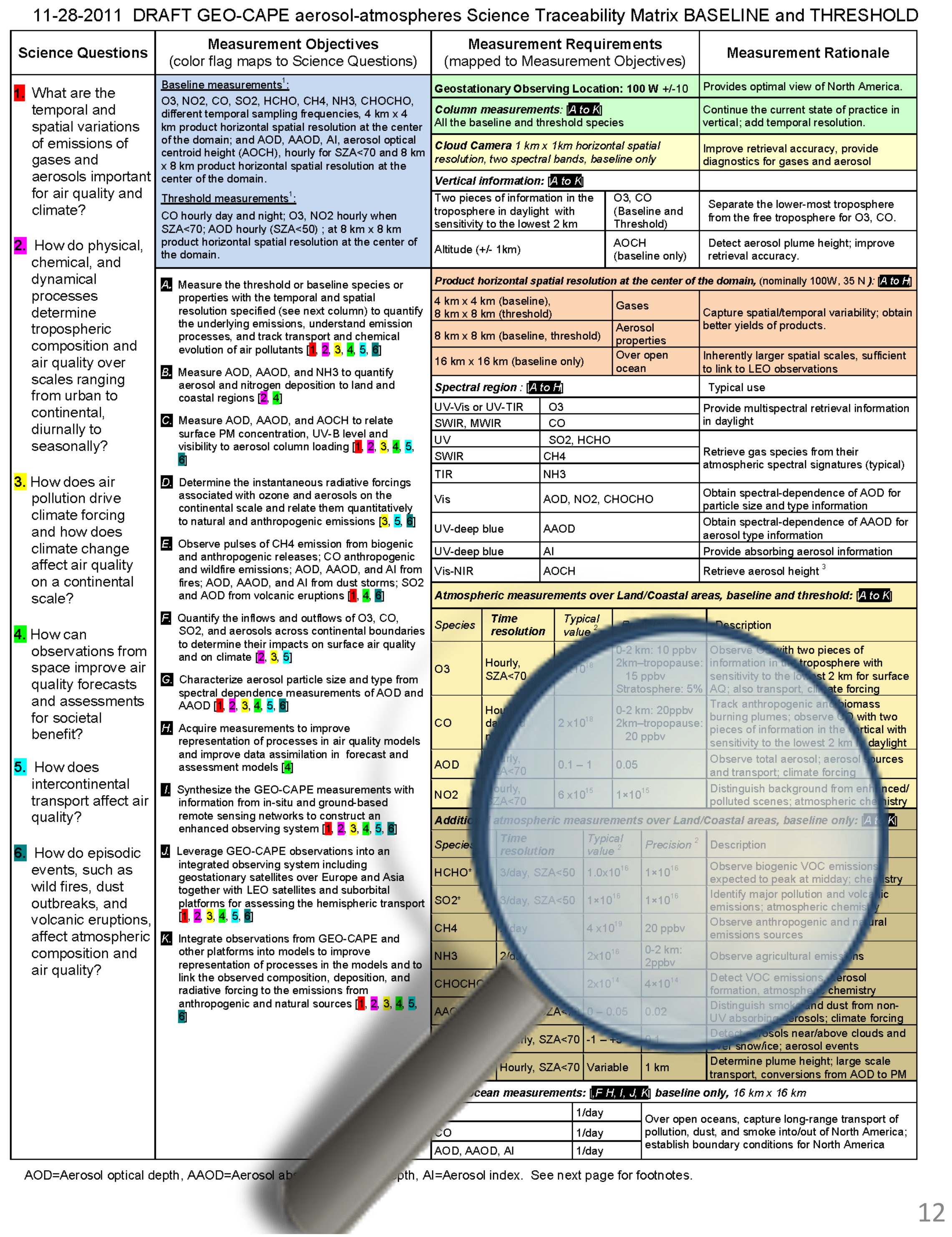
- **Boresight at 33.76°N, 92.85°W**





Location	N/S (km)	E/W (km)	GSA (km^2)	VZA (°)
Boresight	2.0	4.8	9.5	39.3
36.5°N, 100°W	2.1	4.8	10.1	42.4
Washington, DC	2.3	5.1	11.3	48.0
Seattle	3.2	6.2	16.8	61.7
Los Angeles	2.1	5.6	11.3	48.0
Boston	2.5	5.5	13.0	53.7
Miami	1.8	4.9	8.6	33.2
San Juan	1.7	5.6	9.2	37.4
Mexico City	1.6	4.7	7.7	23.9
Can. tar sands	4.1	5.6	20.8	67.0
Juneau	6.1	9.1	33.3	75.3

Air quality requirements from the GEO-CAPE Science Traceability Matrix



11-28-2011 DRAFT GEO-CAPE aerosol-atmospheres Science Traceability Matrix BASELINE and THRESHOLD

Science Questions

1. What are the temporal and spatial variations of emissions of gases and aerosols important for air quality and climate?
2. How do physical, chemical, and dynamical processes determine tropospheric composition and air quality over scales ranging from urban to continental, diurnally to seasonally?
3. How does pollution drive climate forcing and how does climate change affect air quality on a continental scale?
4. How can observations from space improve air quality forecasts and assessments for societal benefit?
5. How does intercontinental transport affect air quality?
6. How do episodic events, such as wild fires, dust outbreaks, and volcanic eruptions, affect atmospheric composition and air quality?

Measurement Objectives (color flag maps to Science Questions)

Baseline measurements[1]:
O3, NO2, CO, SO2, HCHO, CH4, NH3, CHOCHO, different temporal sampling frequencies, 4 km x 4 km product horizontal spatial resolution at the center of the domain; and AOD, AAOD, AI, aerosol optical centroid height (AOCH), hourly for SZA<70 and 8 km x 8 km product horizontal spatial resolution at the center of the domain.

Threshold measurements[1]:
CO hourly day and night; O3, NO2 hourly when SZA<70; AOD hourly (SZA<50) ; at 8 km x 8 km product horizontal spatial resolution at the center of the domain.

A. Measure the threshold or baseline species or properties with the temporal and spatial resolution specified (see next column) to quantify the underlying emissions, understand emission processes, and track transport and chemical evolution of air pollutants [1, 2, 3, 4, 5, 6]
B. Measure AOD, AAOD, and NH3 to quantify aerosol and nitrogen deposition to land and coastal regions [2, 4]
C. Measure AOD, AAOD, and AOCH to relate surface PM concentration, UV-B level and visibility to aerosol column loading [1, 2, 3, 4, 5, 6]
D. Determine the instantaneous radiative forcings associated with ozone and aerosols on the continental scale and relate them quantitatively to natural and anthropogenic emissions [3, 5, 6]
E. Observe pulses of CH4 emission from biogenic and anthropogenic releases; CO anthropogenic and wildfire emissions; AOD, AAOD, and AI from fires; AOD, AAOD, and AI from dust storms; SO2 and AOD from volcanic eruptions [1, 4, 6]
F. Quantify the inflows and outflows of O3, CO, SO2, and aerosols across continental boundaries to determine their impacts on surface air quality and on climate [2, 3, 5]
G. Characterize aerosol particle size and type from spectral dependence measurements of AOD and AAOD [1, 2, 3, 4, 5, 6]
H. Acquire measurements to improve representation of processes in air quality models and improve data assimilation in forecast and assessment models [4]
I. Synthesize the GEO-CAPE measurements with information from in-situ and ground-based remote sensing networks to construct an enhanced observing system [1, 2, 3, 4, 5, 6]
J. Leverage GEO-CAPE observations into an integrated observing system including geostationary satellites over Europe and Asia together with LEO satellites and suborbital platforms for assessing the hemispheric transport [1, 2, 3, 4, 5, 6]
K. Integrate observations from GEO-CAPE and other platforms into models to improve representation of processes in the models and to link the observed composition, deposition, and radiative forcing to the emissions from anthropogenic and natural sources [1, 2, 3, 4, 5, 6]

Measurement Requirements (mapped to Measurement Objectives)		Measurement Rationale
Geostationary Observing Location: 100 W +/-10		Provides optimal view of North America.
Column measurements: [A to K] All the baseline and threshold species		Continue the current state of practice in vertical; add temporal resolution.
Cloud Camera *1 km x 1km horizontal spatial resolution, two spectral bands, baseline only*		Improve retrieval accuracy, provide diagnostics for gases and aerosol
Vertical information: [A to K]		
Two pieces of information in the troposphere in daylight with sensitivity to the lowest 2 km	O3, CO (Baseline and Threshold)	Separate the lower-most troposphere from the free troposphere for O3, CO.
Altitude (+/- 1km)	AOCH (baseline only)	Detect aerosol plume height; improve retrieval accuracy.
Product horizontal spatial resolution at the center of the domain, (nominally 100W, 35 N): [A to H]		
4 km x 4 km (baseline), 8 km x 8 km (threshold)	Gases	Capture spatial/temporal variability; obtain better yields of products.
8 km x 8 km (baseline, threshold)	Aerosol properties	
16 km x 16 km (baseline only)	Over open ocean	Inherently larger spatial scales, sufficient to link to LEO observations
Spectral region : [A to H]		Typical use
UV-Vis or UV-TIR	O3	Provide multispectral retrieval information in daylight
SWIR, MWIR	CO	
UV	SO2, HCHO	Retrieve gas species from their atmospheric spectral signatures (typical)
SWIR	CH4	
TIR	NH3	
Vis	AOD, NO2, CHOCHO	Obtain spectral-dependence of AOD for particle size and type information
UV-deep blue	AAOD	Obtain spectral-dependence of AAOD for aerosol type information
UV-deep blue	AI	Provide absorbing aerosol information
Vis-NIR	AOCH	Retrieve aerosol height[3]

Atmospheric measurements over Land/Coastal areas, baseline and threshold: [A to K]

Species	*Time resolution*	*Typical value*[2]	*Precision*[2]	Description
O3	Hourly, SZA<70	x10^{18}	0-2 km: 10 ppbv 2km–tropopause: 15 ppbv Stratosphere: 5%	Observe O3 with two pieces of information in the troposphere with sensitivity to the lowest 2 km for surface AQ; also transport, climate forcing
CO	Hourly, day and night	2 x10^{18}	0-2 km: 20ppbv 2km–tropopause: 20 ppbv	Track anthropogenic and biomass burning plumes; observe CO with two pieces of information in the vertical with sensitivity to the lowest 2 km in daylight
AOD	Hourly, SZA<70	0.1 – 1	0.05	Observe total aerosol; aerosol sources and transport; climate forcing
NO2	Hourly, SZA<70	6 x10^{15}	1×10^{15}	Distinguish background from enhanced/ polluted scenes; atmospheric chemistry

Additional atmospheric measurements over Land/Coastal areas, baseline only: [A to K]

Species	*Time resolution*	*Typical value*[2]	*Precision*[2]	Description
HCHO*	3/day, SZA<50	1.0x10^{16}	1×10^{16}	Observe biogenic VOC emissions expected to peak at midday; chemistry
SO2*	3/day, SZA<50	1×10^{16}	1×10^{16}	Identify major pollution and volcanic emissions; atmospheric chemistry
CH4	2/day	4 x10^{19}	20 ppbv	Observe anthropogenic and natural emissions sources
NH3	2/day	2x10^{16}	0-2 km: 2ppbv	Observe agricultural emissions
CHOCHO		2x10^{14}	4×10^{14}	Detect VOC emissions, aerosol formation, atmospheric chemistry
AAOD	SZA<70	0 – 0.05	0.02	Distinguish smoke and dust from non-UV absorbing aerosols; climate forcing
	Hourly, SZA<70	-1 – +5	0.1	Detect aerosols near/above clouds and over snow/ice; aerosol events
	Hourly, SZA<70	Variable	1 km	Determine plume height; large scale transport, conversions from AOD to PM

ocean measurements: [F H, I, J, K] ***baseline only,*** *16 km x 16 km*

	1/day	Over open oceans, capture long-range transport of pollution, dust, and smoke into/out of North America; establish boundary conditions for North America
CO	1/day	
AOD, AAOD, AI	1/day	

AOD=Aerosol optical depth, AAOD=Aerosol ab… …pth, AI=Aerosol index. See next page for footnotes.

Infrared species

Ultraviolet/ visible species (GOME, SCIA, OMI, OMPS, TEMPO, etc.)

Atmospheric measurements over Land/Coastal areas, baseline and threshold: [A to K]				
Species	***Time resolution***	*Typical value* [2]	*Precision* [2]	Description
O3	Hourly, SZA<70	9×10^{18}	0-2 km: 10 ppbv 2km–tropopause: 15 ppbv Stratosphere: 5%	Observe O3 with two pieces of information in the troposphere with sensitivity to the lowest 2 km for surface AQ; also transport, climate forcing
CO	Hourly, day and night	2×10^{18}	0-2 km: 20ppbv 2km–tropopause: 20 ppbv	Track anthropogenic and biomass burning plumes; observe CO with two pieces of information in the vertical with sensitivity to the lowest 2 km in daylight
AOD	Hourly, SZA<70	0.1 – 1	0.05	Observe total aerosol; aerosol sources and transport; climate forcing
NO2	Hourly, SZA<70	6×10^{15}	1×10^{15}	Distinguish background from enhanced/ polluted scenes; atmospheric chemistry

Additional atmospheric measurements over Land/Coastal areas, baseline only: [A to K]				
Species	***Time resolution***	*Typical value* [2]	*Precision* [2]	Description
HCHO*	3/day, SZA<50	1.0×10^{16}	1×10^{16}	Observe biogenic VOC emissions, expected to peak at midday; chemistry
SO2*	3/day, SZA<50	1×10^{16}	1×10^{16}	Identify major pollution and volcanic emissions; atmospheric chemistry
CH4	2/day	4×10^{19}	20 ppbv	Observe anthropogenic and natural emissions sources
NH3	2/day	2×10^{16}	0-2 km: 2ppbv	Observe agricultural emissions
CHOCHO*	2/day	2×10^{14}	4×10^{14}	Detect VOC emissions, aerosol formation, atmospheric chemistry
AAOD	Hourly, SZA<70	0 – 0.05	0.02	Distinguish smoke and dust from non-UV absorbing aerosols; climate forcing
AI	Hourly, SZA<70	-1 – +5	0.1	Detect aerosols near/above clouds and over snow/ice; aerosol events
AOCH	Hourly, SZA<70	Variable	1 km	Determine plume height; large scale transport, conversions from AOD to PM

Baseline and threshold data products

Species/Products	Required Precision	Temporal Revisit
0-2 km O_3 (Selected Scenes) Baseline only	10 ppbv	2 hour
Tropospheric O_3	10 ppbv	1 hour
Total O_3	3%	1 hour
Tropospheric NO_2	1.0×10^{15} molecules cm^{-2}	1 hour
Tropospheric H_2CO	1.0×10^{16} molecules cm^{-2}	3 hour
Tropospheric SO_2	1.0×10^{16} molecules cm^{-2}	3 hour
Tropospheric $C_2H_2O_2$	4.0×10^{14} molecules cm^{-2}	3 hour
Aerosol Optical Depth	0.10	1 hour

- **Minimal set of products sufficient for constraining air quality**
- **Across Greater North America (GNA): 18°N to 58°N near 100°W, 67°W to 125°W near 42°N**
- **Data products at urban-regional spatial scales**
  - **Baseline ≤ 60 km^2 at center of Field Of Regard (FOR)**
  - **Threshold ≤ 300 km^2 at center of FOR**
- **Temporal scales to resolve diurnal changes in pollutant distributions**
- **Geolocation uncertainty of less than 4 km**
- **Mission duration, subject to instrument availability**
  - **Baseline 20 months**
  - **Threshold 12 months**

TEMPO science questions

1. What are the temporal and spatial variations of **emissions** of gases and aerosols important for air quality and climate?
2. How do physical, chemical, and dynamical **processes** determine tropospheric composition and air quality over scales ranging from urban to continental, diurnally to seasonally?
3. How does air pollution drive **climate** forcing and how does climate change affect air quality on a continental scale?
4. How can observations from space improve **air quality forecasts and assessments** for societal benefit?
5. How does **intercontinental transport** affect air quality?
6. How do **episodic events**, such as wild fires, dust outbreaks, and volcanic eruptions, affect atmospheric composition and air quality?

Air quality and health

TEMPO's hourly measurements allow better understanding of the complex chemistry and dynamics that drive **air quality on short timescales**. The density of TEMPO data is ideally suited for data assimilation into chemical models for both air quality forecasting and for better constraints on emissions that lead to air quality exceedances. Planning is underway to combine TEMPO with regional air quality models to **improve EPA air quality indices and to directly supply the public with near real time pollution reports and forecasts through website and mobile applications**. As a case study, an OSSE for the Intermountain West was performed to explore the potential of geostationary ozone measurements from TEMPO to improve monitoring of ozone exceedances and the role of background ozone in causing these exceedances (Zoogman *et al*. 2014).

Aerosols and clouds

Aerosols TEMPO's launch algorithm for retrieving aerosols will be based upon the OMI aerosol algorithm that uses the sensitivity of near-UV observations to particle absorption to retrieve **absorbing aerosol index** (AAI), **aerosol optical depth** (AOD) and **single scattering albedo** (SSA). TEMPO will derive its pointing from one of the **GOES-17** or **GOES-17** satellites and is thus automatically co-registered. TEMPO may be used together with the advanced baseline imager (ABI) instrument, particularly the 1.37μm bands, for aerosol retrievals, reducing AOD and fine mode AOD uncertainties from 30% to 10% and from 40% to 20%.

Clouds The launch cloud algorithm is be based on the rotational Raman scattering (RRS) cloud algorithm that was developed for OMI by NASA GSFC. Retrieved cloud pressures from OMCLDRR are not at the geometrical center of the cloud, but rather at the optical centroid pressure (OCP) of the cloud. **Additional** cloud products are possible using the O_2-O_2 collision complex and/or the O_2 *B* band.

TEMPO instrument concept

- **Measurement technique**
  - Imaging grating spectrometer measuring solar backscattered Earth radiance
  - Spectral band & resolution: 290-490 + 540-740 nm @ 0.6 nm FWHM, 0.2 nm sampling
  - 2 2-D, 2k×1k, detectors image the full spectral range for each geospatial scene
- **Field of Regard (FOR) and duty cycle**
  - Mexico City/Yucatan, Cuba to the Canadian oil sands, Atlantic to Pacific
  - Instrument slit aligned N/S and swept across the FOR in the E/W direction, producing a radiance map of Greater North America in one hour
- **Spatial resolution**
  - 2.1 km N/S × 4.7 km E/W native pixel resolution (9.8 km^2)
  - Co-add/cloud clear as needed for specific data products
- **Standard data products and sampling rates**
  - Most sampled hourly, including eXceL O_3 (troposphere, PBL)
  - NO_2, H_2CO, $C_2H_2O_2$, SO_2 sampled hourly (average results for ≥ 3/day if needed)
  - Nominal spatial resolution 8.4 km N/S × 4.7 km E/W at center of domain (can often measure 2.1 km N/S × 4.7 km E/W)
  - Measurement requirements met up to 50^o for SO_2, 70^o SZA for other products

Traffic, biomass burning

Morning and evening higher-frequency scans The optimized data collection scan pattern during mornings and evenings provides multiple advantages for addressing TEMPO science questions. The increased frequency of scans coincides with peaks in vehicle miles traveled on each coast.

Biomass burning The unexplained variability in ozone production from fires is of particular interest. The suite of NO_2, H_2CO, $C_2H_2O_2$, O_3, H_2O, and aerosol measurements from TEMPO is well suited to investigating how the chemical processing of primary fire emissions effects the secondary formation of VOCs and ozone. For particularly important fires it is possible to command special TEMPO observations at even shorter than hourly revisit time, as short as 10 minutes.

NO_x studies

Lightning NO_x Interpretation of satellite measurements of tropospheric NO_2 and O_3, and upper tropospheric HNO_3 lead to an overall estimate of 6 ± 2 Tg N y^{-1} from lightning [Martin et al., 2007]. TEMPO measurements, including tropospheric NO_2 and O_3, can be made for time periods and longitudinal bands selected to coincide with large thunderstorm activity, including outflow regions, with fairly short notice.

Soil NO_x Jaeglé et al. [2005] estimate 2.5 - 4.5 TgN y^{-1} are emitted globally from nitrogen-fertilized soils, still highly uncertain. The US a posteriori estimate for 2000 is 0.86 ± 1.7 TgN y^{-1}. For Central America it is 1.5 ± 1.6 TgN y^{-1}. They note an underestimate of NO release by nitrogen-fertilized croplands as well as an underestimate of rain-induced emissions from semiarid soils.

TEMPO is able to follow the temporal evolution of emissions from croplands after fertilizer application and from rain-induced emissions from semi-arid soils. Higher than hourly time resolution over selected regions may be accomplished by special observations. Improved constraints on soil NO_x emissions may also improve estimated of lightning NO_x emissions [Martin *et al*. 2000].

Spectral indicators

Fluorescence and other spectral indicators Solar-induced fluorescence (SIF) from chlorophyll over both land and ocean will be measured. In terrestrial vegetation, chlorophyll fluorescence is emitted at red to far-red wavelengths (~650-800 nm) with two broad peaks near 685 and 740 nm, known as the red and far-red emission features. Oceanic SIF is emitted exclusively in the red feature. SIF measurements have been used for studies of **tropical dynamics**, **primary productivity**, the length of the **carbon uptake** period, and **drought responses**, while ocean measurements have been used to detect red **tides** and to conduct studies on the physiology, phenology, and productivity of **phytoplankton**. TEMPO can retrieve both red and far-red SIF by utilizing the property that SIF fills in solar Fraunhofer and atmospheric absorption lines in backscattered spectra normalized by a reference (*e.g.*, the solar spectrum) that does not contain SIF.

TEMPO will also be capable of measuring **spectral indices developed for estimating foliage pigment contents and concentrations**. Spectral approaches for estimating pigment contents apply generally to leaves and not the full canopy. A single spectrally invariant parameter, the **Directional Area Scattering Factor** (DASF), relates canopy-measured spectral indices to pigment concentrations at the leaf scale.

UVB TEMPO measurements of daily UV exposures build upon heritage from OMI and TROPOMI measurements. Hourly cloud measurements from TEMPO allow taking into account diurnal cloud variability, which has not been previously possible. The OMI UV algorithm is based on the TOMS UV algorithm. The specific products are the downward spectral irradiance at the ground (in W m^{-2} nm^{-1}) and the erythemally weighted irradiance (in W m^{-2}).

Data products, science studies (the Green Paper), special operations

Volcanic **SO_2** (column amount and plume altitude is a potential research product. Diurnal out-going **shortwave radiation and cloud forcing** is a potential research product.

Nighttime **"city lights"** products, which represent anthropogenic activities at the same spatial resolution as air quality products, may be produced twice per day (late evening and early morning) as a research product. Meeting TEMPO measurement requirements for NO_2 (visible) implies the sensitivity for city lights products over the CONUS within a 2-hour period at 2×4.5 km^2 to 1.1×10^{-8} W cm^{-2} sr^{-1} μm^{-1}.

Several additional **first-measurement molecules** are being studied.

H_2O will be produced at launch from the 7v vibrational polyad at 445 nm. Water vapor retrieved from the visible spectrum has good sensitivity to the planetary boundary layer, since the absorption is optically thin, and is available over both the land and ocean. The hourly coverage of TEMPO will greatly improve the knowledge of water vapor's diurnal cycle and make rapid variations in time readily observed.

Halogens

BrO will be produced at launch, assuming stratospheric AMFs. Scientific studies will correct retrievals for tropospheric content. **IO** was first measured from space by SAO using SCIAMACHY spectra [Saiz-Lopez *et al*., 2007]. It will be produced as a scientific product, particularly for coastal studies, assuming AMFs appropriate to lower tropospheric loading.

The atmospheric chemistry of halogen oxides over the ocean, and in particular in coastal regions, can play important roles in ozone destruction, oxidizing capacity, and dimethylsulfide oxidation to form cloud-condensation nuclei [Saiz-Lopez and von Glasow, 2012]. The budgets and distribution of reactive halogens along the coastal areas of North America are poorly known. Therefore, providing a measure of the budgets and diurnal evolution of coastal halogen oxides is necessary to understand their role in atmospheric photochemistry of coastal regions. Previous ground-based observations have shown enhanced levels (at a few pptv) of halogen oxides over coastal locations with respect to their background concentrations over the remote marine boundary layer [Simpson et al., 2015]. Previous global satellite instruments lacked the sensitivity and spatial resolution to detect the presence of active halogen chemistry over mid-latitude coastal areas. TEMPO observations together with atmospheric models will allow examination of the processes linking ocean halogen emissions and their potential impact on the oxidizing capacity of coastal environments of North America.

TEMPO also performs **hourly measurements of one of the world's largest salt lakes: the Great Salt Lake in Utah**. Measurements over Salt Lake City show the highest concentrations of BrO over the globe. Hourly measurement at a high spatial resolution can improve understanding of BrO production in salt lakes.

TEMPO launch algorithms

NO_2, SO_2, H_2CO, $C_2H_2O_2$ vertical columns

- Direct fitting to TEMPO radiances
- AMF-corrected reference spectra, Ring effect, etc.
- DOAS option available to trade more speed for less accuracy, if necessary
- Research products could include H_2O, BrO, OClO, IO

O_3 profiles, tropospheric O_3

- eXceL optimal-estimation method developed @ SAO for GOME, OMI
- May be extended to SO_2, especially volcanic SO_2

TOMS-type ozone retrieval included for heritage

Aerosol products from OMI heritage: AOD, AAOD, Aerosol Index

- Advanced/improved products likely developed @ GSFC, U. Nebraska

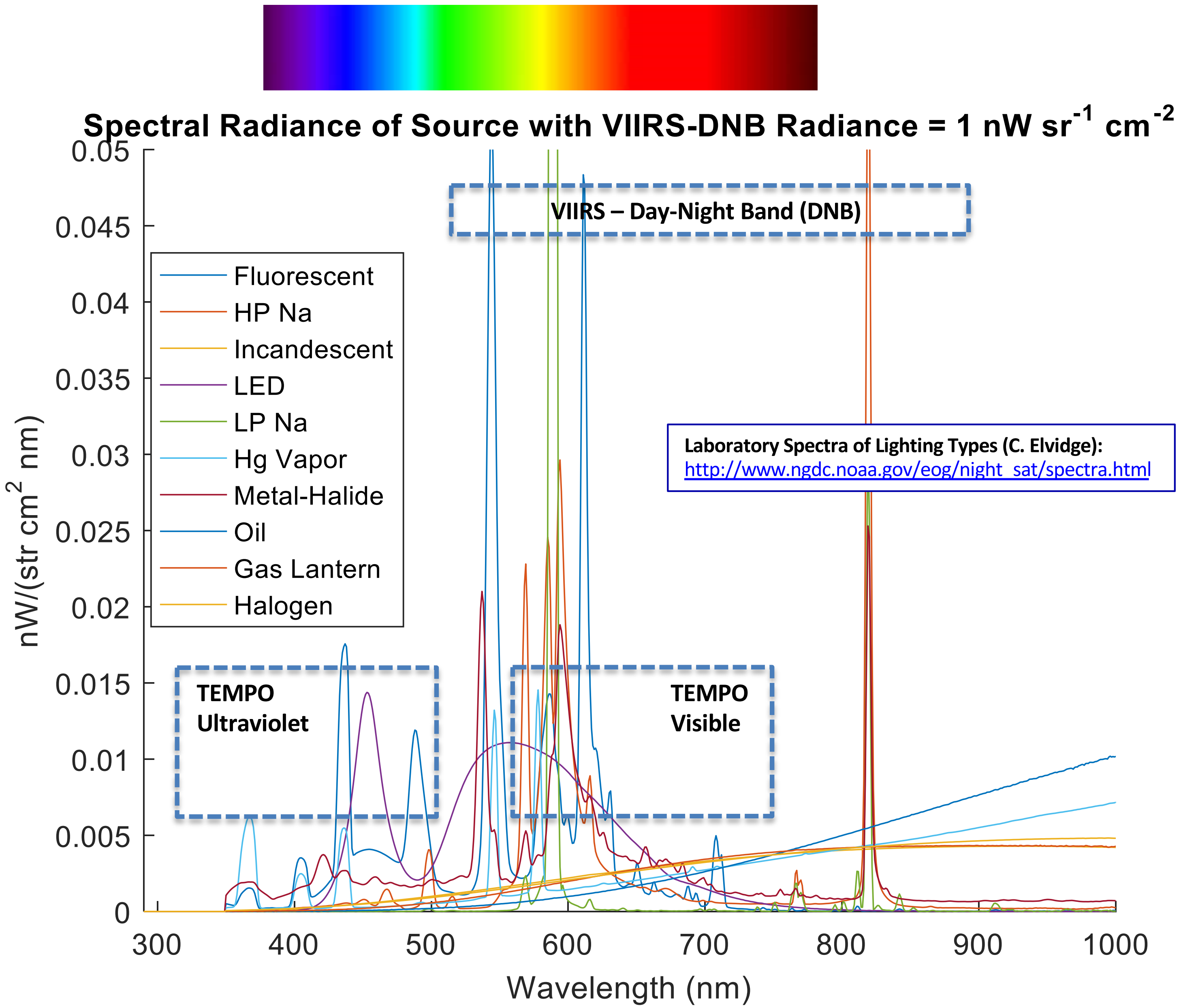
Cloud Products from OMI heritage: CF, CTP

- Advanced/improved products likely developed @ GSFC

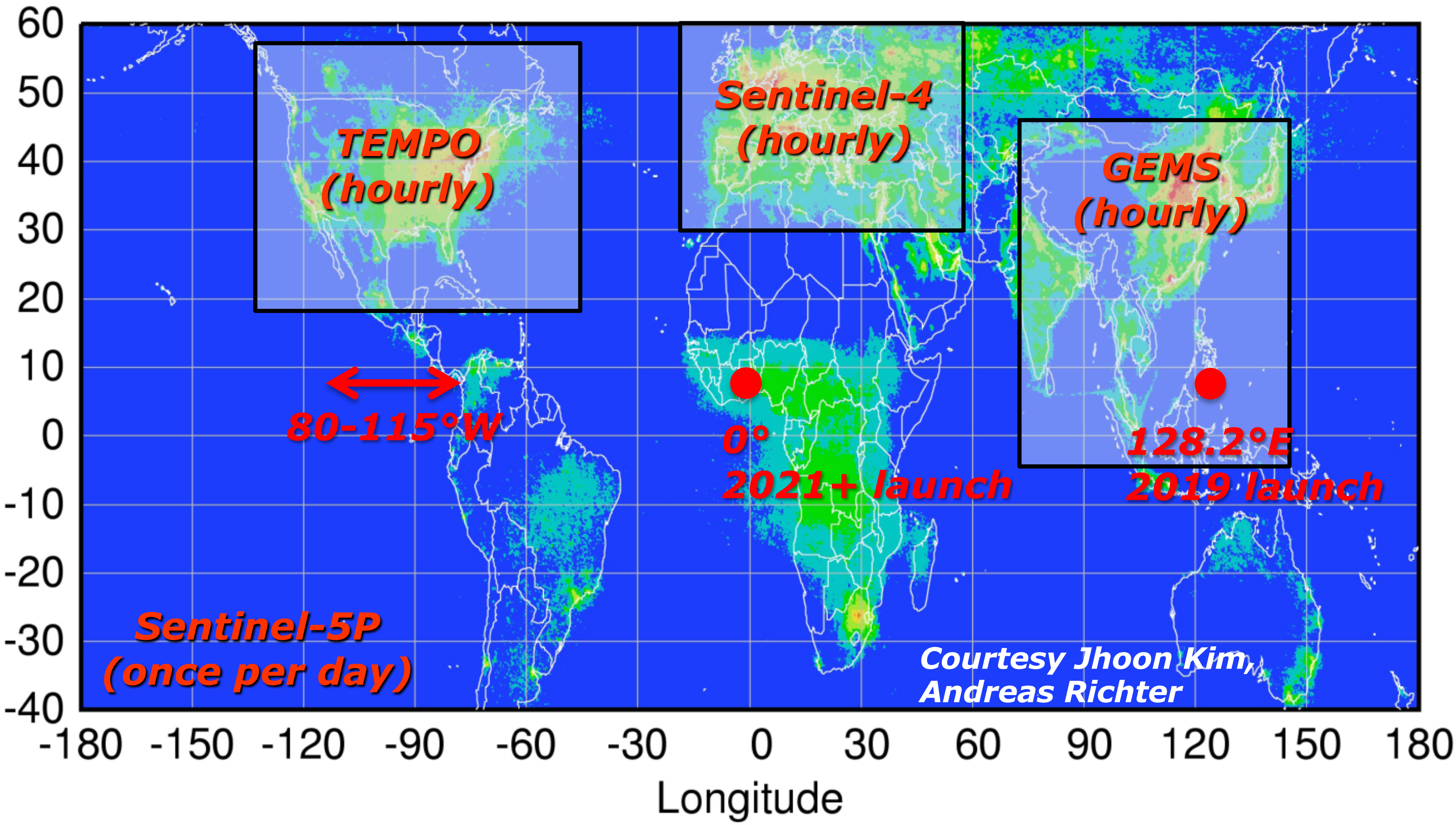
UVB research product based on OMI heritage (FMI, GSFC)

Nighttime research products include city lights

City lights spectroscopic signatures



Global pollution monitoring constellation



Low Earth orbit: Sun-synchronous nadir heritage

Instrument	Detectors	Spectral Coverage [nm]	Spectral Res. [nm]	Ground Pixel Size [km^2]	Global Coverage
GOME-1 (1995-2011)	Linear Arrays	240-790	0.2-0.4	40×320 (40×80 zoom)	3 days
SCIAMACHY (2002-2012)	Linear Arrays	240-2380	0.2-1.5	$30 \times 30/60/90$ $30 \times 120/240$	6 days
OMI (2004)	2-D CCD	270-500	0.42-0.63	13×24 - 42×162	daily
GOME-2a,b (2006, 2012)	Linear Arrays	240-790	0.24-0.53	40×80 (40×10 zoom)	near-daily
OMPS-1 (2011)	2-D CCDs	250-380	0.42-1.0	50×50	daily

Previous experience (since 1985 at SAO and MPI)

Scientific and operational measurements of pollutants O_3, NO_2, SO_2, H_2CO, $C_2H_2O_2$ (& CO, CH_4, BrO, OClO, ClO, IO, H_2O, O_2-O_2, Raman, aerosol, ….)

The TEMPO Green Paper

Smithsonian NASA

Chemistry, physics, and meteorology experiments with the Tropospheric Emissions: Monitoring of Pollution instrument
Now at: https://www.cfa.harvard.edu/atmosphere/publications.html

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NORMAL TIME RESOLUTION STUDIES

- **Air quality and health**
- **Ultraviolet exposure**
- **Biomass burning**
- **Synergistic GOES-16/17 Products**
- **Advanced aerosol products**
- **Soil NO_x after fertilizer application and after rainfall**
- **Solar-induced fluorescence from chlorophyll**
- **Foliage studies**
- **Mapping NO_2 and SO_2 dry deposition at high resolution**
- **Crop and forest damage from ground-level ozone**
- **Halogen oxide studies in coastal and lake regions**
- **Air pollution from oil and gas fields**
- **Night light measurements resolving lighting type**
- **Ship tracks, drilling platform plumes, and other concentrated sources.**
- **Water vapor studies**
- **Volcanoes**
- **Socio-economic studies**
- **National pollution inventories**
- **Regional and local transport of pollutants**
- **Sea breeze studies for Florida and Cuba**
- **Transboundary pollution gradients**
- **Transatlantic dust transport**

HIGH TIME RESOLUTION EXPERIMENTS

- **Lightning NO_x**
- **Morning and evening higher-frequency scans**
- **Dwell-time studies and temporal selection to improve detection limits**
- **Exploring the value of TEMPO in assessing pollution transport during upslope flows**
- **Tidal effects on estuarine circulation and outflow plumes**
- **Air quality responses to sudden changes in emissions**